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# STRONG TRANSVERSE FIELDS IN δ-SPOTS

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**Abstract.** Spectroscopic measurements of the strength and direction of transverse magnetic fields in six δ-spots are presented. The field direction is determined by the relative strength of the $\pi$- and $\sigma$-components at different polarizer orientations, and is, with one exception, parallel to the neutral line and as strong as the umbral field. Field strengths determined by line splitting are as high as 3980 G.

## 1. Introduction

In 1966, we noted the presence of elongated sunspots in highly active regions (Zirin and Lackner, 1969). While isolated spots show radial penumbral structure, complex groups with spots crowded together distort this, often showing strong tangential fibril structure in the penumbra. In 1972 Zirin and Tanaka (1973) saw strong shear both in H$\alpha$ and white light along the neutral line of the great August active region, and Livingston (private communication) found linear alignments of strong field areas along the sheared neutral line. The strong suspicion that the elongated spots and the sheared neutral line of δ-spots with strong field gradients had transverse fields was confirmed by spectra published by Tanaka (1991), showing fields of 4300 G in an elongated spot in a δ-configuration. This fact is important in understanding solar flares, which almost all occur in such areas.

Observations with vector magnetographs have demonstrated the existence of the sheared fields. Because there are still some researchers who doubt the validity of vector field measurements, and the vector magnetographs saturate for very strong fields, in 1990 we began a program of obtaining spectra in such regions. In the transverse Zeeman effect, the unsplit $\pi$-component is linearly polarized in the field direction, while the $\sigma$-components, which are split, are linearly polarized perpendicular to the field vector. Our first measurements immediately showed strong splitting along the neutral line when a polaroid was placed perpendicular to it. When the polaroid was rotated to lie along the neutral line, a single $\pi$-component appeared. Remarkably, the splitting in the neutral line region was as great as that in the sunspot umbrae. We had, of course, expected this result from the tremendous distortion of the penumbral structure in these regions, as well as the fact that the δ-spots invariably push together, compressing the penumbral fields. One cannot doubt the field values obtained by measuring the splitting with a ruler. Observatories without transverse magnetographs can easily measure these fields with a spectrograph.

This result has several important consequences:

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It confirms the existence of strong sheared fields in $\delta$-spots, parallel to the neutral line.

It confirms the existence of sharp discontinuities in the field direction that we find in videomagnetograms.

It shows that strong magnetic fields do not necessarily lead to the darkening of sunspots, at least if they are horizontal. We have already published an example (Zirin, 1988, Figure 10.13).

## 2. Data

Sunspots were observed with the 3-m Littrow Coudé spectrograph and a slit jaw camera recording in the wing of H$\alpha$. Both spectrum and slit jaw image were recorded continuouslyn with Cohu CCD cameras on S–VHS videotape. Although many spectra were underexposed due to observer inexperience, usable data were obtained for seven spot groups and presentable data for three or four. The images were digitized for measurement. Since only the splitting is measured here, video recording is quite adequate and, because of its high time resolution, gives high spatial resolution as we scan.

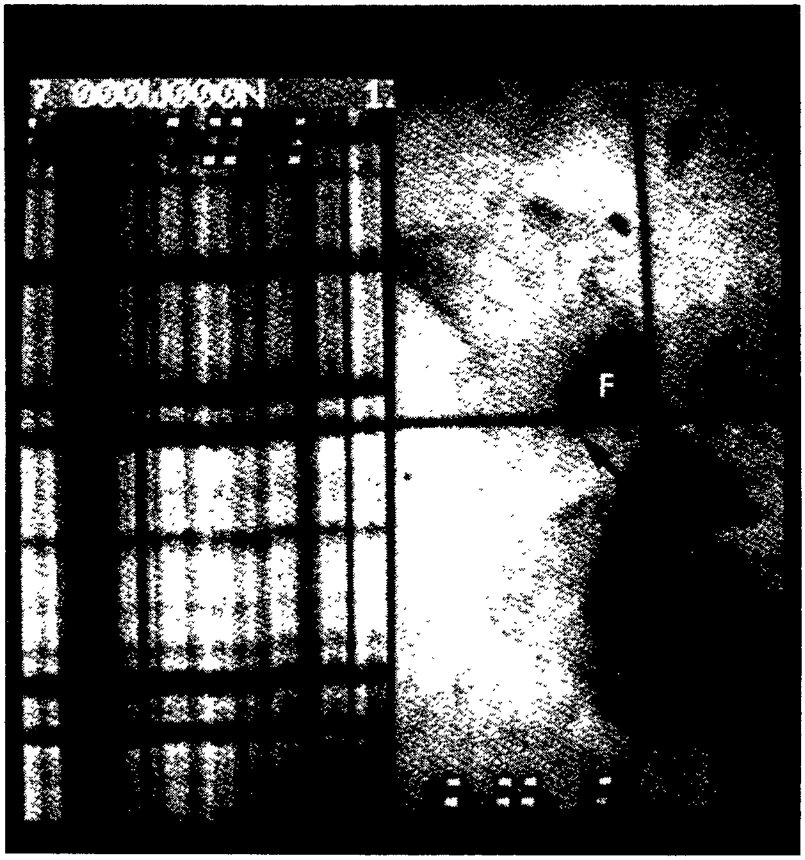


Fig. 1. Splitting in the great spot of June 1991. A slit jaw image in the wing of field gradient in the neutral line of the configuration; the spot *F* just above the slit is opposite polarity. The arrow indicates the direction of the polarizer through which the spectrum is taken. The strong splitting (3500 G) between umbra and cross wire corresponds to field perpendicular to the arrow and parallel to the neutral line. The vertical crosswire seen in the slit jaw image corresponds to the vertical line $\frac{1}{3}$ of the way from the left in the spectrum.

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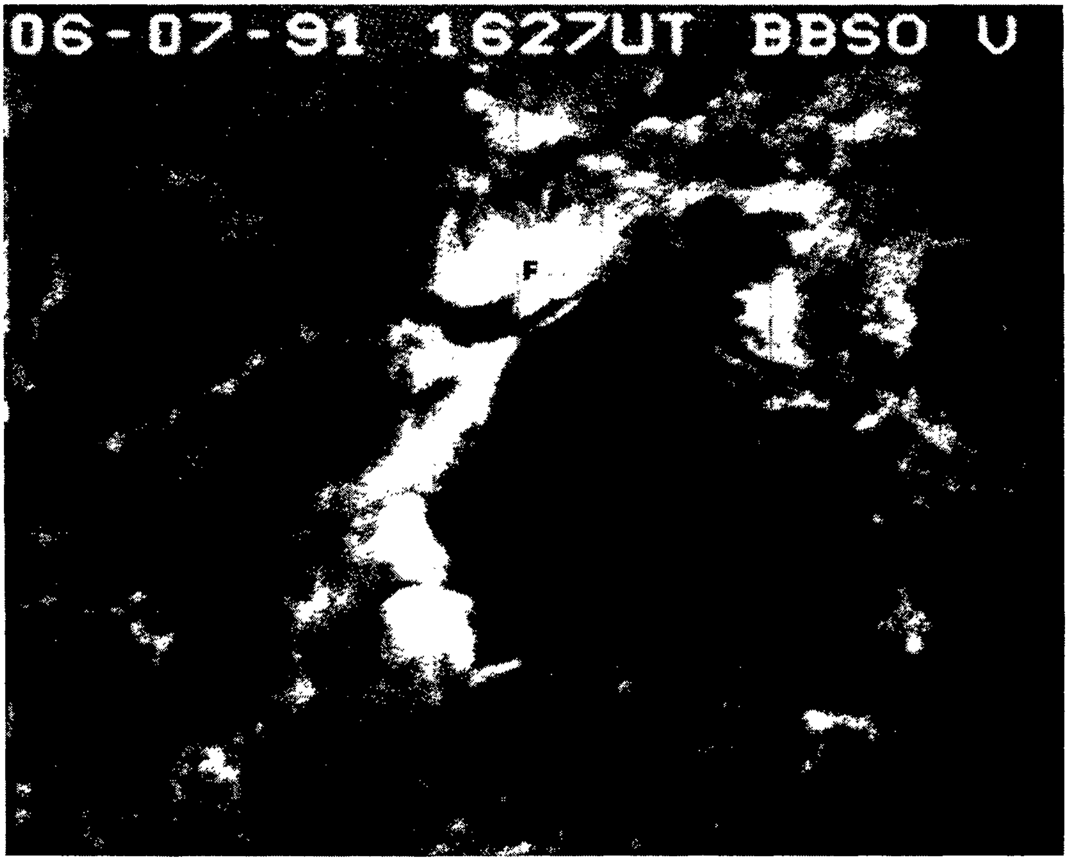


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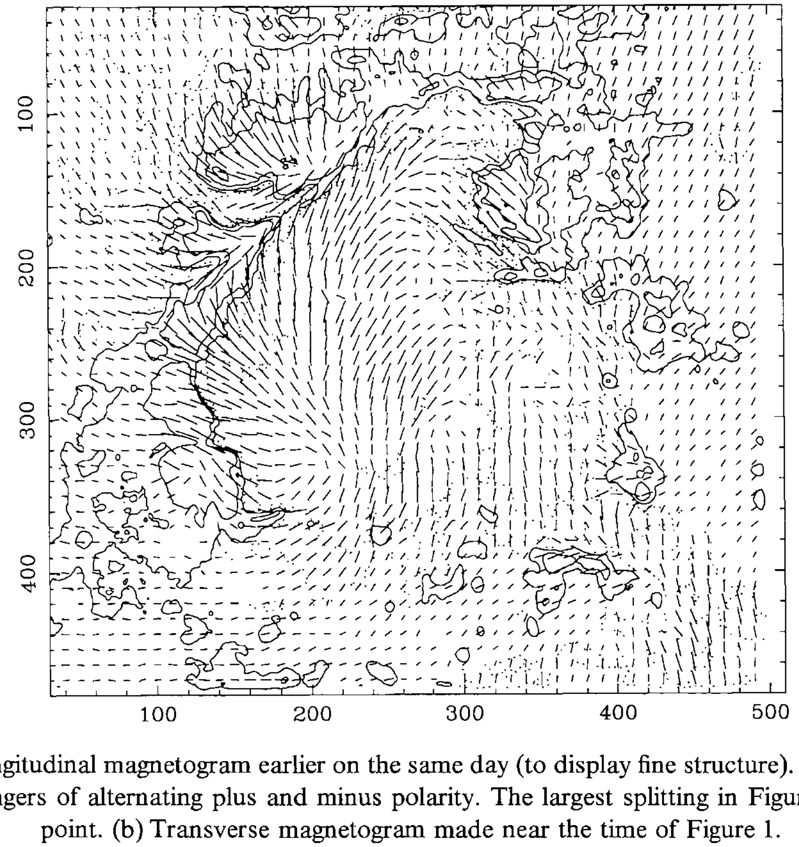


Fig. 2. (a) Longitudinal magnetogram earlier on the same day (to display fine structure). The neutral line is paralleled by fingers of alternating plus and minus polarity. The largest splitting in Figure 1 occurs at this point. (b) Transverse magnetogram made near the time of Figure 1.

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In one case (June 9, 1991), data were obtained with a $1024 \times 1024$ CCD; these spectra are better, but the lower cadence restricts spatial resolution.

Figure 1 shows splitting in a great, highly active spot observed June 7, 1991. This region was notable for a $\delta$-configuration produced by a follower spot marked $F$ very close to the main umbra. Figure 1 shows a slit jaw image in the wing of H$\alpha$ at right, the slit horizontal and intersected by two vertical fiducial cross hairs. The spot $F$ is to the upper left of the cross, and the sheared neutral line lies between it and the main body of the spot group. The arrow indicates the direction of a linear polarizer. At left we see the spectrum at 5250; the slit clips the opposite-polarity umbra at left and passes through a sharp field gradient in the neutral line of the configuration to its right. The strong splitting (3480 G) between umbra and fiducial corresponds to field perpendicular to the arrow and parallel to the neutral line. The splitting decreases abruptly to the right of the fiducial as the split passes out of the channel.

Figure 2(a) shows a longitudinal field magnetogram taken earlier in the day. The positive polarity spot $F$ is marked; we see that there is a sharp field gradient just below $F$, accompanied by a truly remarkable series of longitudinal field reversals, which are different from anything we have seen. The transverse magnetograms are plotted in Figure 2(b); it is readily seen that strong transverse field was recorded in the direction indicated by the spectroscopic data. This kind of measurement calibrates the vector


Fig. 3. Splitting in the same region on June 3, 3100 G. The horizontal field is very strong, exceeding that in the umbra.

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magnetogram and confirms the field direction deduced. In the spectral scans of the group one readily recognizes normal penumbra; the field strength falls off sharply going out from the umbra, as seen at the left edge of Figure 1, and the $\pi$-component dominates with a radial slit. This contrasts with the sheared field, which decreases slowly if at all as we pass through the penumbra.

Color images of the transverse field (Wang and Zirin, 1992) show the transverse field concentrated in a series of narrow lanes. These are not seen here, possibly because of fortuitous positioning of the slit along these lanes, or lower resolution of the spectra.

Figures 3 and 4 show similar spectrum-slit jaw pairs in the same spot on June 9. There is rapid change in the field strength.

Figure 5 shows the splittings in a complex penumbra and large spot on October 2, 1991. At the extreme left, near the arrow indicating the polaroid orientation, we see a normal penumbral field decrease. To the right of the same umbra we see a wide penumbral splitting, about 3500 G, no weaker than the field in the spot. The field direction is perpendicular to the polaroid arrow, therefore radial from the spot. But a short distance to the right, the two $\sigma$-components are abruptly replaced by a single unshifted $\pi$-component, indicating field parallel to the polaroid axis. Thus there is a sharp transition between fields oriented at 90° to each other, without the presence of an umbra. Note the contrast of this with the extended penumbra outside the δ-spot.

Fig. 4. A slight shift in slit position reveals a sharp decrease in the transverse field strength to 2500 G, but the shear extends over a larger area.

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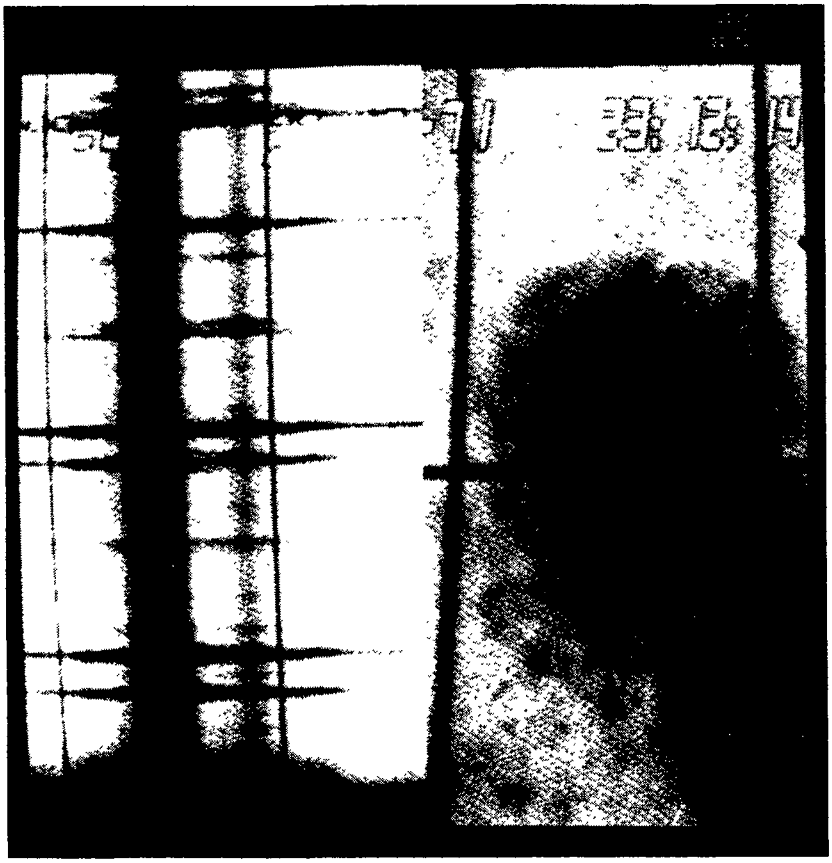

Fig. 5. Sharp rotation of the transverse field angle in spot observed October 2, 1991. Left of the umbra, the normal penumbral field decreases radially. Right of the umbra, we have large penumbral splitting of 3500 G, abruptly changing to a single unshifted component, indicating field parallel to the polaroid axis. The weak $\sigma$-component shows that the field there is almost as strong, but rotated nearly 90 deg.

Figure 6 shows an exception in the same spot group; a $\delta$-spot without shear. The slit is positioned between two umbrae of opposite polarity, and $\sigma$-components are seen with the polaroid parallel to the neutra line. Therefore the field lines run directly between the two spots and there is no shear. There were no flares here, either, nor was there the H$\alpha$ shear or brightening common in sheared $\delta$-configurations.

We have now measured such fields in 7 complex spot groups, with the same result in all cases, namely, the field as strong as the umbrae and (except for the case in Figure 6) parallel to the neutral line. In another case, we measured transverse field near an umbra next to a filament or field inversion. There, without another spot to anchor the field, the transverse splitting was smaller than in the umbra. The largest transverse field measured (May 12, 1991) was 3980 G.

## 3. Conclusions

We find that in all sheared $\delta$-spots (picked by shear or close spacing) strong transverse field comparable in strength to the umbral field is observed, as measured by the splitting of transverse $\sigma$-components. Thus large-sheared fields are important in highly

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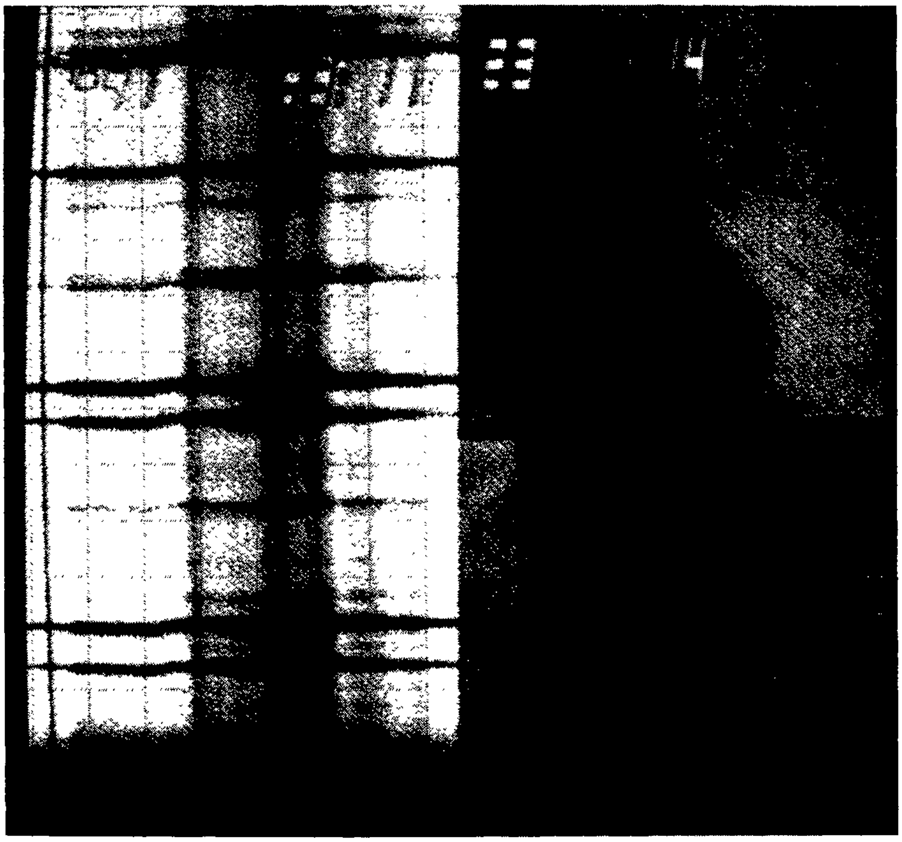

Fig. 6. Splitting in a different part of the same group, between two spots of opposite polarity, but transverse field is directed so as to directly connect the two spots. An unusual condition.

flare-productive spots. In all but one case the field was directed parallel to the neutral line. We find that the strongest transverse fields are confined to long, extremely narrow channels. It is clear that, unlike vertical fields, strong transverse fields do not produce umbral darkening, although they always corresponds to penumbra.

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